TITLE
0001   GENERATOR FOR AGILE FREQUENCY SIGNALS

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BACKGROUND OF THE INVENTION

0003   The present invention relates to methods and apparatus for generating and transmitting agile frequency test signals, such as frequency hopped signals, to receivers under test and particularly to provide test signals that enable testing of receiver performance beyond nominal receiver performance.

0004   Agile frequency signals are signals that have rapidly changing frequency and time characteristics and include, for example, frequency hopping signals. Frequency hopping is a form of spread-spectrum signaling where, for short instances of time, relatively narrowband signals are transmitted as short bursts with the carrier frequency for each burst tuned to a different one of a set of carrier frequencies than the ones of the carrier frequencies used for the previous burst and the next burst. The sequence of frequencies that is used for a sequence of bursts is known as the hopping sequence. The carrier frequency transmission at any particular instant of time for one burst is therefore different than the carrier frequency transmission at the previous instant of time for the previous burst and similarly is different than the carrier frequency transmission at the next instant of time for the next burst. While the bandwidth for any particular burst may be narrow, the bandwidth for the whole set of frequencies in the hopping sequence can be very large. Typically a frequency hop system hops over a bandwidth many times the bandwidth of the individual hop signal bandwidth. Bluetooth for example has a 1 MHz signal bandwidth and hops over 80 MHz. Some military radios have a 25 kHz signal bandwidth with thousands of hop frequencies covering over 50 MHz. The frequency hoppers in use today hop over at least 8 times the bandwidth of the signal bandwidth.

0005   Frequency hopping systems with changing frequency transmissions have a number of advantages over the fixed frequency transmissions of non-hopping systems. If a particular hop frequency, in the set of frequencies used in a hopping sequence, happens to include a frequency that

is regularly occupied by another interfering radio signal, the frequency hopping system detects the occupied status and functions to retransmit the burst of data at a different frequency. Also, the frequency hopping system detects the regularly occupied frequencies for any particular installation and reestablishes a hopping sequence that excludes the occupied frequency from the set of frequencies in the hopping sequence.

0006 Frequency hopping systems are more secure than fixed frequency systems because the interception of frequency hopped signals is significantly more difficult than interception of fixed frequency signals, particularly when the hopping sequence is not known in advance. If a communication protocol is intended to be secure, such as in military and other secure environments, the hopping sequence and other protocol, specification and standards information is not published and is changed from time to time to support secure operation.

0007 In any environment, the characterization of radios and radio wave signals for frequency hopped systems is difficult because they operate and function over broad bandwidths and because each burst at a particular frequency is of relatively short duration. The characterization of signals for frequency hopped systems is even more difficult when done in a secret environment where the protocol, specification, standards, hopping sequence and other characterizing information is not fully known in advance. A secret environment is common since manufacturers and users of frequency hopping systems often wish to maintain their protocols, specifications, standards and hopping sequences confidential and unpublished.

0008 As the complexity of radios increases, the ability to adequately test the radios becomes more difficult. One common test procedure employs a "golden radio". A golden radio is a radio that operates "nominally", where "nominally" is loosely defined to mean an "average", a "mean" or an "expected" operation. Each radio under test (test radio) is tested to ensure acceptable communication with the golden radio. If a test radio communicates well with the golden radio, then the test radio is accepted and if not, the test radio is rejected. This golden radio test method is limited because in actual use, radios will communicate with other radios that do not behave nominally. Large failure rates (for example, as high as 30%) often result in actual use when only golden radio testing is employed.

0009 Other common test procedures employ test equipment in the form of signal generators

for generating test signals for testing radios where the test signals are selected to have nominal values determined, for example, from specifications established for the transmit and receive characteristics of the test radios. Test equipment such as the Agilent E4438C, Agilent E8267C and the Tektronix SMIQ series can generate transmit signals to test standard wireless communications system such as 2, 2.5 and 3G cellular telephone systems and 802.11 wireless networks. The Tektronix SMIQ can generate a Bluetooth frequency hopped signal over a frequency band, but the band is narrower than the specified 80 MHz available for Bluetooth. All of these signal generators use symbols that are either random in nature or specified in the standard to produce a known test signal. These test systems do not achieve satisfactory testing since they do not adequately test the range of operation actually encountered by radios in a real environment where many radios having some non-nominal characteristics (all having passed nominal tests, however) fail to communicate satisfactorily.

0010   Because of the difficulty of testing frequency hopping radios, the above and many other systems employ "hop-in-place" analysis where the test does not occur with frequency hopping or even if some hopping occurs, the hopping is not permitted to extend over the full hopping bandwidth available. These systems, therefore, do not adequately test frequency hopping radios.

0011   It is desired to test the radios with transmitted signals having signal parameters that cover the range of the specified values and tolerances of the radios with accurate control over the signal attributes including sequences, symbols and parameters.

0012   Various signal simulators have been proposed that deal with the transmission problems encountered in communications. Patent 6,438,357 simulates the path loss encountered in the transmission of cellular telephone signals. Patent 6,307,879 provides a method of compensating for distortion in the radio transmission process. Patent 6,058,261 simulates Doppler, delay, multipath and delay spread encountered in the transmission process. None of these patents discuss changing the fundamental transmitted signal parameters to represent the range of parameters that are present when many different radios are communicating in actual operation in a non-test environment. While changes in the carrier frequency have been implemented by simulating Doppler, such a change is limited and does not allow change of frequency over the range of operation permitted by the specification for the radio. In the case of frequency hopped signals, the inadequacy is even greater since the carrier frequency changes for each hop.

0013 Patent 6,128,474 tests the diversity reception of a multiple antenna radio. Patents 6,243,576 and 6,112,067 discuss a standard stimulus/response test system where the system transmits a known signal to a test device, such as a cellular telephone, and receives the response signal transmitted by the test device to ensure the test device properly received and processed the test signal. While these systems test against the known signal, such systems do not test the range of signals likely to be encountered in a real environment.

0014 Other systems simulate signals for testing radars. Patent 6,075,480 covers a system to simulate Doppler shift on complex radar signals. Patent 5,117,230 records and plays back radar signals using signal processing to simulate the target encounter. Patent 4,168,502 simulates a radar signal digitally to simulate a range of target velocity and acceleration. None of these patents deal with changing the signal parameters over the range of the radio specification other than those unique to the changes encountered in the transmission/reception process and hence they do not deal with the actual parameter variations from radio to radio in real communication systems.

0015 The known test systems provide limited testing of radios without adequately testing the range of variables likely to be encountered in communications systems and therefore, they are not fully adequate for the communication industry.

0016 Accordingly, in order to meet the demands of the communication industry, improved methods and apparatus are needed for generating agile frequency signals for broadband systems.

SUMMARY

0017 The present invention is a transmitter for an agile frequency test signal for testing a receiver of a test radio. The transmitter includes a signal component source for providing a test sequence for the test signal, test symbols for the test signal and test parameters for the test signal. A signal generator digitally processes the test sequence, the test symbols and test parameters to form the test signal and the transmitter transmits the test signal to the receiver of the test radio. The test signals are generated with specified and known signal parameter values that enable testing of the receivers using the modulation method employed by the communication system of the receiver and for performance beyond nominal performance established by receiver specifications.

0018 In one embodiment, the agile frequency test signals are transmitted and the receiving

radio is monitored to judge the proper functionality in response to the test signals. The test radio is typically a frequency hop radio receiver and the test signal is a frequency hopped signal that has been generated with signal parameters at specified and known values. Also, digital signal processing is used to modulate the signal carrier with message symbols using the modulation method employed by the communication system.

0019   In one embodiment, the system receives a signal from a transmitter and demodulates the received signal to recover the message symbols. The system then uses these recovered symbols to regenerate the test signal with specified signal parameters. In the case of frequency hop signals, the demodulating process also measures the hop frequencies so that the regenerated test signals hop with the recovered hopping sequence, that is, the test signal has the same frequency hop channels and the same message symbols as the original transmitted signal.

0020   The parameters that are specified will vary with each modulation type and radio specification. Common parameters include carrier frequency, frequency drift, modulation parameters, interference signals and amplitude ripple.

0021   In the case of digital communication signals, the parameters also include symbol rate and clock jitter. In the case of burst signals like TDMA and frequency hopped signals, the parameters include burst duration, interval, timing, burst frequency and frequency error.

0022   The steps in the process are: a) the radio transmits a message that is intercepted by the signal collection and analysis part of the system b) the signal is demodulated to recover the hop frequencies and the message symbols, c) these hop frequencies, message symbols and user input on signal parameter values are used to regenerate the signal, d) the signal is retransmitted and e) the receiver function is monitored to verify the receiver is functioning properly. The transmit and receive test radios may be the same or different radios of the same specification.

0023   The signal generation includes in some embodiments adding in interference signals and noise to provide a known, calibrated way to simulate the effects of the signal being transmitted via antennas. In addition in some embodiments, the signal is faded to simulate the signal amplitude variations due to a moving radio receiver. Similarly, signal processing is used to impart the effects of multipath interference on the signal.

0024   This test of the test radio in one embodiment is an operator speaking into the

microphone of the test radio transmitter, the system receiving and regenerating the signal and the operator listening to the test radio receiver to verify that the operator's message is heard on the radio speaker.

0024b. In another test, the signal from a defective radio is received, recorded and analyzed. The analysis determines signal problems. These problems include, for example, close-in interference or spurs, amplitude ripple, precarriers and bad rise/fall characteristics. These types of problems can exist individually or in any combination. To determine the impact of these types of problems on the radio performance, especially when multiple problems exist simultaneously, the problems are isolated and selectively removed using digital signal processing to form one or more corrected signals. The resultant corrected signals are transmitted to determine the radio performance in response to the corrected signals. The sequencing of the corrected signals is used to determine which ones, and possible all, of the problems are adversely affecting performance of the receiving radio.

0025 The foregoing and other objects, features and advantages of the invention will be apparent from the following detailed description in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

0026 FIG 1 is a block diagram showing the test signal components used for test signal generation and test signal transmission.

0027 FIG 2 shows a transmitter and receiver in the same radio where the transmitter provides the source of test signal components and the receiver receives the test signals generated from the test signal components.

0028 FIG 3 shows a transmitter and receiver in different radios of the same specification where the transmitter provides the source of test signal components and the receiver receives the test signals generated from the test signal components.

0029 FIG 4 shows how the system can be used with a single test radio, as in FIG 2, connected to the system via wires instead of transmit and receive antennas and alternatively how the system can be used with separate transmit and receive radios, as in FIG 3, using wires instead of transmit and receive antennas.

0030 FIG 5 presents details of the signal receive and analysis subsystems.

0031 FIG 6 presents details of the signal generation and transmit subsystems.

0032 FIG 7 shows the digital signal processing used to identify the samples associated with the signal segment and to calculate the power spectrum of the segment.

0033 FIG 8 shows the digital signal processing used to calculate the carrier frequency and the bandwidth of the segment.

0034 FIG 9 is a block diagram of the digital signal processing algorithm used to calculate the signal symbol rate.

0035 FIG 10 is a typical AM waveform for an FSK signal segment.

0036 FIG 11 is a typical FM waveform for an FSK signal segment.

0037 FIG 12 is a typical FM waveform and the idealized representation of the waveform.

0038 FIG 13 is a representation of a typical hop sequence showing frequency vs. time.

0039 FIG 14 is a spectrogram of a typical hop sequence showing frequency vs. time with signal power indicated by image intensity.

0040 FIG 15 depicts a histogram of dTOT values as compiled and analyzed to show the first major peak and following peaks.

0041 FIG 16 shows an expansion of the first major peak of FIG 15 with three bins used to find the center of mass of the histogram.

0042 FIG 17 shows the details of the process to regenerate the frequency hop signal.

0043 FIG 18 shows the process to record, correct and play a signal from a defective radio and test it on a receive radio.

DETAILED DESCRIPTION

0044 FIG 1 is a block diagram showing the signal generator **15** with test signal components **10** used for test signal processing **11** and test signal transmission **12**. The test signal transmission **12** transmits an agile frequency test signal for testing a radio under test (test radio) **101**. The test radio **101** is analyzed by test **99** to determine acceptable or non-acceptable performance in response to the agile test signal. The transmitter includes a source for the test signal components **10** that provides a test sequence for the test signal, test symbols for the test signal and test parameters for the test signal. The test signal processing **11** digitally processes the test sequence, the test symbols and test

parameters to form the test signal. The test signal transmission **12** transmits the test signal to the receiver of the test radio. The test signals are generated with specified and known values that enable testing of the receiver and radios under test using the modulation method employed by the communication system of the radios under test and the testing is for performance beyond nominal performance. The agile frequency test signals transmitted by the test signal transmission **12** to the receiving radio are monitored to test the proper functionality of the receiving radio in response to the test signals. The test radio is typically a frequency hop radio and the test signal is a frequency hopped signal that has been generated with signal parameters at specified and known values. Also, digital signal processing is used to modulate the signal carrier with message symbols using the modulation method employed by the communication system.

0045 A typical frequency hopping sequence used by the radio **101** is shown in FIG 13. The signal of FIG 13 shows the signal time on the X axis and the signal frequency on the Y axis. The hopping sequence for the first ten hops in FIG. 13 is indicated in the following TABLE 1 as H1, H2, ..., H10. For clarity, FIG. 13 does not represent the amplitude of the signals at the different hop frequencies.

0046

TABLE 1	
HOP	**f_c (MHz)**
H1	52
H2	38
H3	67
H4	34
H5	32
H6	64
H7	79
H8	31
H9	81
H10	44

0047   Another typical frequency hopping sequence for radio **101**, the device under test, is shown in FIG 14. The signal of FIG 14 shows the signal time on the X axis and the signal frequency on the Y axis and the signal power in the image intensity. The signal of FIG 14 is unique in that the hop bandwidth is greater than the channel frequencies. The hopping sequence for the first twenty hops in FIG. 14 is indicated in the following TABLE 2 as H1, H2, ..., H20.

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TABLE 2			
HOP	f_c **(MHz)**	**HOP**	f_c **(MHz)**
1	75	11	39
2	18	12	75
3	78	13	18
4	24	14	78
5	90	15	18
6	6	16	78
7	39	17	24
8	24	18	90
9	90	19	6
10	6	20	39

0049   FIG 2 is an example of the FIG 1 system where a transmitter and receiver are in the same radio **101** and the radio **101** communicates through an air interface. In FIG 2 in the first step, the radio **101** transmits a signal **114** to the system down converter **104** via antennas **102** and **103**. The down converter **104** has sufficient bandwidth to capture the entire frequency range of the signal **114**. In the case of a frequency hop signal, the down converter will have the bandwidth to capture all of the hop frequencies of interest for the radio communication system under test.

0050   The IF output of the converter **104** is digitized with A/D converter **105**. The down converter band limits the IF signal to reduce aliasing in the A/D converter **105** to an acceptable level. The sample rate is at least twice the highest frequency of the frequency hopped signal with enough

bits of resolution to provide the dynamic range to permit analysis.

0051   If the input signal 114 is transmitted at a low radio frequency, the down converter 104 is not necessary. For example, if the highest frequency of the input signal is 30 MHz, the received signal may be sampled directly with a sample rate of 60 Msamples/second or higher to obey the Nyquist criteria. Similarly, alias sampling can be used for signal frequencies that are greater than half the sample rate. For example, if the input signal 114 is from 110 – 125 MHz, the input signal can be sampled at 100 Msamples/second to create a digitized signal on the output of the A/D converter 105 of FIG 2 from 10 – 25 MHz.

0052   The digital signal is processed with the digital signal processing (DSP) analysis 106 to extract the frequency, symbols and other information. In the case of a frequency hopped signal, this extraction is done independently on each hop.

0053   The storage memory 109 stores the test signal components including a test sequence that is determined by the sequence of each different frequency, test symbols and test parameters determined by the DSP analysis 106. The digital signal processing (DSP) generator 110 digitally processes the test sequence, the test symbols and test parameters to form an agile test signal. The test parameters and other inputs are provided in some embodiments by the control 100. If the highest transmitted RF signal frequency is lower than half of the D/A sample rate, up converter 112 is not needed. The agile test signal is D/A converted in D/A converter 111, up-converted in up-converter 112 and transmitted over the air interface by antenna 113 to antenna 102 of the test radio 101. The agile test signals are generated with specified and known values that enable testing of the radio 101 using the modulation method employed by the communication system of the radio 101 and the testing is for performance beyond nominal performance. The agile frequency test signals transmitted to the receiving test radio 101 are monitored by test 99 to test the proper functionality of radio 101 in response to the test signals. The radio 101 is typically a frequency hop radio and the test signal is a frequency hopped signal that has been generated with signal parameters at specified and known values.

0054   FIG 3 shows a transmitter and receiver in different radios, radios 101-1 and 101-2, of the same specification. The transmitter of radio 101-1 provides the source of test signal components and the receiver of radio 101-2 receives the agile frequency test signals generated from the test signal

generator.

0055 The radios **101-1** and **101-2** communicate through an air interface. In FIG 3 in the first step, the radio **101-1** transmits a signal **114** to the system down converter **104** via antennas **102-1** and **103**. The down converter **104** has sufficient bandwidth to capture the entire frequency range of the signal **114**. In the case of a frequency hop signal, the down converter will have the bandwidth to capture all of the hop frequencies of interest for the radio communication system under test.

0056 The IF output of the converter **104** is digitized with A/D converter **105**. The down converter band limits the IF signal to reduce aliasing in the A/D converter **105** to an acceptable level. The sample rate is at least twice the highest frequency of the frequency hopped signal with enough bits of resolution to provide the dynamic range to permit analysis.

0057 If the input signal **114** is transmitted at a low radio frequency, the down converter **104** is not necessary. For example, if the highest frequency of the input signal is 30 MHz, the received signal may be sampled directly with a sample rate of 60 Msamples/second or higher to obey the Nyquist criteria. Similarly, alias sampling can be used for signal frequencies that are greater than half the sample rate. For example, if the input signal **114** is from 110 – 125 MHz, the input signal can be sampled at 100 Msamples/second to create a digitized signal on the output of the A/D converter **105** of FIG 3 from 10 – 25 MHz.

0058 The digital signal is processed with the digital signal processing analysis **106** to extract the frequency **13** and symbols **108**. In the case of a frequency hopped signal, this extraction is done independently on each hop.

0059 The storage memory **109** stores the test signal components including a test sequence that is determined by the sequence of each different frequency **13**, test symbols **108** and test parameters determined by the DSP analysis **106**. The digital signal processing (DSP) generator **110** digitally processes the test sequence, the test symbols and test parameters to form an agile test signal. The test parameters and other inputs are provided in some embodiments by the control **100**. If the highest transmitted RF signal frequency is lower than half of the D/A sample rate, up converter **112** is not needed. The agile test signal is D/A converted in D/A converter **111**, up-converted in up-converter **112** and transmitted over the air interface by antenna **113** to antenna **102-2** of the test radio **101-2**. The agile test signals are generated with specified and known values that enable testing of the

radio **101-2** using the modulation method employed by the communication system of the radios **101-1** and **101-2** and the testing is for performance beyond nominal performance. The agile frequency test signals transmitted to the receiving test radio radios **101-2** is monitored by test **99** to test the proper functionality of radio **101-2** in response to the test signals. The radios **101-1** and **101-2** are typically frequency hop radios and the test signal is a frequency hopped signal that has been generated with signal parameters at specified and known values.

0060 FIG 4 is an example of the FIG 2 and FIG 3 systems where transmitters and receivers are in the same radio **101**, or in different and the radios **101-1** and **101-1**, that do not communicate through an air interface but communicate through a wired interface. In FIG 4 in the first step, the radio **101** transmits a signal **114** through splitter/coupler **119** to the system down converter **104** via hard-wired line **128**. Alternatively, in FIG 4 in the first step, the radio **101-1** transmits a signal **114'** to the system down converter **104** via hard-wired line **128'**. The down converter **104** has sufficient bandwidth to capture the entire frequency range of the signal from splitter/coupler **119**. In the case of a frequency hop signal, the down converter will has the bandwidth to capture all of the hop frequencies of interest for the radio communication system under test.

0061 The IF output of the converter **104** is digitized with A/D converter **105**. The down converter band limits the IF signal to reduce aliasing in the A/D converter **105** to an acceptable level. The sample rate is at least twice the highest frequency of the frequency hopped signal with enough bits of resolution to provide the dynamic range to permit analysis.

0062 If the input signal **114** is transmitted at a low radio frequency, the down converter **104** is not necessary. For example, if the highest frequency of the input signal is 30 MHz, the received signal may be sampled directly with a sample rate of 60 Msamples/second or higher to obey the Nyquist criteria. Similarly, alias sampling can be used for signal frequencies that are greater than half the sample rate. For example, if the input signal **114** is from 110 – 125 MHz, the input signal can be sampled at 100 Msamples/second to create a digitized signal on the output of the A/D converter **105** of FIG 2 from 10 – 25 MHz.

0063 The digital signal is processed with the digital signal processing (DSP) analysis **106** to extract the frequency **13** and symbols **108**. In the case of a frequency hopped signal, this extraction is done independently on each hop.

0064   The storage memory **109** stores the test signal components including a test sequence that is determined by the sequence of each different frequency **13,** test symbols **108** and test parameters determined by the DSP analysis **106**. The digital signal processing (DSP) generator **110** digitally processes the test sequence, the test symbols and test parameters to form an agile test signal. The test parameters and other inputs are provided in some embodiments by the control **100**. If the highest transmitted RF signal frequency is lower than half of the D/A sample rate, up converter **112** is not needed. The agile test signal is D/A converted in D/A converter **111,** up-converted in up-converter **112**. In one alternative, the up-converted signal **115** is connected over the hard-wired line **129** to splitter/coupler **119** to the receive input of the test radio **101**. In another alternative, the up-converted signal **115'** is connected over the hard-wired line **129'** to the receive input of the test radio **101-2**. The agile test signals are generated with specified and known values that enable testing of the radio **101** or radio **101-2** using the modulation method employed by the communication system of the radio **101** or radios **101-1** and **101-2** and the testing is for performance beyond nominal performance. The agile frequency test signals transmitted to the receiving test radio **101** are monitored by test **99**, or transmitted to the receiving test radio **101-2** are monitored by test **99'** to test the proper functionality of radio **101** or radio **101-2** in response to the test signals. The radios **101, 101-1** and **101-2** are typically frequency hop radios and the test signals are frequency hopped signals that have been generated with signal parameters at specified and known values.

0065 In FIG 5, the unit **134** performs broadband frequency agile signal characterization on the signals from radio **101-1**. An input signal from radio **101-1** is received by the agile signal characterization unit **134** through a receiving antenna **103**. The receiving antenna **103** captures the radio frequency signal transmitted through the air interface by antenna **102** of radio **101-1**. When transmitted through the air interface, the input signal will likely require amplification by amplifier **120**. However, if the received input signal is within the proper amplitude range, the amplifier **120** can be eliminated. The signal from the amplifier **120** is down converted, when necessary, by the radio frequency to intermediate frequency converter, RF/IF **121,** to provide an input to the A/D converter **105**. After down conversion in RF/IF **121,** when required, the resulting converted signal is digitized in A/D converter **105** to form a digitized signal. The sample rate of the A/D converter **105** is at least twice the highest frequency of the frequency hopped signal with enough bits of resolution

to provide a dynamic range that permits analysis. With a direct-wired connection, 8 bits of resolution are sufficient. Using antennas, as shown in FIG 5, that are subject to environmental interference signals and noise, at least 12 bits of resolution are preferred. The digitized signal is stored in the memory **122** where it becomes available for processing by the digital signal processor (DSP) **106.**

0066 In FIG 5, the radio **101-1** has the same specifications as the radio **101-2.** The radio **101-1** produces a radio frequency input signal which is captured and processed for broadband analysis by signal processing components. The broadband analysis performed commences using an amplitude component to determine the start and stop times of each of the segments of the input signal. For each segment identified by the amplitude component, a frequency component determines the frequency of the segment. A signal component converts each input segment having an input form to a converted segment having a converted form. The converted form facilitates further processing. An analysis of the converted segment is performed using a parameter component to determine signal parameters of each segment individually and to determine signal parameters of multiple segments collectively so as to characterize the input signal.

0067 The analysis performed in FIG 5 occurs without requiring prior knowledge of the radio specifications, protocols, standards or other similar information about the radio **101-1.** Accordingly, the FIG 5 analysis is particularly suitable for analyzing radios that are not operating within their specifications or that are otherwise operating poorly, for analyzing unknown signals and for analyzing signals without need for knowledge of the radio specification.

0068 In FIG 5, the generator for agile frequency signals **134** uses the signal components stored in storage memory **109** to generate agile frequency signals. The digital signal processor **110** performs the processing to create the agile signals and stores the results in memory **123.** The test parameters and other inputs are provided in some embodiments by the control **100.** The results from memory **123** are converted to analog signals in D/A converter **111,** filtered in low pass filter **124** up-converted in converter **112** (if necessary), amplified in amplifier **125** and transmitted through antenna **113** to antenna **102-2** of test radio **101-2.** The received test signal in radio **101-2** is tested by test **99.**

0069 In FIG 6, the AMPLITUDE component **224-1** determines the amplitude of the input signal appearing on the output 7 from the front end unit **229** of FIG 5 using the amplitude

measurement block **209**. Various algorithms may be used in measurement block **209** to measure the amplitude of the input signal. One efficient algorithm takes the absolute value of the digitized signal on the output **7**. The threshold detector **210** functions between hops to detect a burst by detecting the first sample that exceeds the threshold. At this point, the threshold detector **210** is disabled or ignored until the signal analysis indicates the burst has stopped.

0070 In parallel with AMPLITUDE component **224-1**, the FREQUENCY component **224-2** determines the frequency of the input signal appearing on the output **7** from the storage memory **109** of FIG 5. The frequency, f_c, is measured in the frequency estimation block **211** and appears at output **213**. The frequency estimation block **211** also estimates the bandwidth, BW, and that estimate appears at output **217**. The measurements in frequency estimation block **211** will be in error when the signal level of the input signal appearing on output **7** is too low. When the signal level exceeds a threshold established by the threshold unit **210** the frequency estimate on output **213** is valid and is then used as the carrier frequency in the down conversion process **215**. If information is known about the channel frequencies of the input signal, in one embodiment, the frequency estimate **213** is rounded to the nearest channel center and the bandwidth **217** is set to the known bandwidth.

0071 Various algorithms can be used to determine the frequency estimate at output **213**. Spectral analysis using a Fast Fourier Transform, FFT, or similar algorithm, is a robust embodiment that uses substantial processing power and requires substantial time to execute. Spectral analysis is preferred when the transmitted signal is received via antennas. With the antenna embodiment, other signals and noise will be intercepted along with the signal from the radio **1**. For example, there are a set of military radios that hop from 30 – 88 MHz. The higher part of this band overlaps with the lower TV channels. By using spectral analysis in the frequency estimation block **211**, the TV and other unwanted signals can be ignored. Spectral analysis is also advantageous when the signal bandwidth is to be estimated.

0072 One preferred embodiment the frequency estimation block **211** uses the algorithm in FIG 7 and FIG 8 which represent the digital signal processing used in the preferred embodiment to calculate the carrier frequency, f_c, of each signal segment. FIG 7 shows the digital signal processing used to identify the samples associated with the signal segment and to calculate the power spectrum of the segment. FIG 8 represents the digital signal processing used to calculate the carrier frequency

and the bandwidth of the segment.

0073 Referring to FIG 7, the absolute value, in block **30**, of the input signal **7** is calculated on each sample and stored in a buffer memory **31**. When 100 samples are collected, the maximum value is determined in block **32**. If this value is greater than a threshold, determined in block **34**, the signal is considered active and the samples at **35**, corresponding to the 100 absolute value samples stored in buffer memory **31**, are stored in a memory **36** which is large enough to accumulate all samples associated with the signal segment. Once stored in memory **36**, the system starts to collect the next 100 samples in buffer memory **31**.

0074 When the max value in the 100 sample buffer memory **31** drops below the threshold determined in block **34**, the signal estimator **46** is commanded at **37** to calculate the power spectrum on all samples in memory **36**. This calculation is done via a windowed digital Fourier transform, DFT in block **38**. One preferred embodiment uses a Hamming window; however, other windows also work well. If memory **36** contains N signals, an N point Hamming window is calculated and multiplied with the signal on a sample by sample basis. The N point DFT of the windowed signal is calculated. A subset of the output DFT bins is processed to determine the strongest signal. The subset is bins from 5 to $N/2 - 5$. The first few bins near DC do not contain signal energy of interest and are ignored. Samples from $N/2$ to $N-1$ are the complex conjugate of samples from 0 to $N/2-1$ and are ignored as their power spectrum is redundant. Samples from $N/2 - 5$ to $N/2 - 1$ are ignored because they contain no useful signal energy. If the signal band is known, just the bins associated with this band can be processed to save processing time and to ignore unwanted signals.

0075 The DFT is used instead of an FFT algorithm so the present system can use all of the samples associated with the segment. The signal frequency accuracy is a function of the time duration of the samples in the DFT. Rounding the number of samples, N, to the nearest FFT size would exclude some samples reducing the measurement accuracy. Alternatively, the N samples can be padded with zeros to bring the buffer length to the nearest FFT size greater than N.

0076   The power spectrum **40** of the bin subset is calculated by taking the magnitude squared **39** of the complex DFT output bins as shown in *Eq 1*. When the time samples in memory **36** have been processed, the memory is reset to start compiling the next segment.

0077   *Eq 1*

$$P(n) = \text{sqrt}(\text{real}\{bin(n)\}^2 + \text{imag}\{bin(n)\}^2), \ 5 < n < N/2\text{-}5$$

0078   The power spectrum bins at **40**, P(n), are processed in block **47** to find the frequency at output **13** and bandwidth at output **17** of the strongest peak in the spectrum. The first step in block **50** is to find the bin number, n_{MAX}, on output **51** and magnitude on output **52** of the strongest bin, P_{MAX}, in P(n) input at **40**. The bins below and above n_{MAX} are examined in block **53** to identify all consecutive bins that have sufficient energy. This examination is done by finding all bins that exceed a threshold based on the P_{MAX}. A typical threshold is to identify all bins exceeding X dB below the max bin. The first bin exceeding the threshold is n_{LOW} and the last bin exceeding the threshold is n_{HIGH}. A typical value of X is around 30 dB. *Eq 2* shows the threshold calculation.

0079 $$\text{Threshold} = 10^{(-X/10)} * P_{MAX}$$ *Eq 2*

0080 The bins associated with the strongest signal, n_{LOW} through n_{HIGH}, are processed to determine the signal frequency at output **13** and bandwidth at output **17**. The signal frequency is estimated with a center of mass algorithm in block **54** as shown in *Eq 3*. The signal power is the value of the denominator of *Eq 3*.

0081

$$fc = \frac{\displaystyle\sum_{n=n_{LOW}}^{n_{HIGH}} \frac{n * fs}{N} P(n)}{\displaystyle\sum_{n=n_{LOW}}^{n_{HIGH}} P(n)} \qquad\qquad Eq\ 3$$

where:

f_c	=	carrier frequency **13** (cycles/second)
f_s	=	sample rate (samples/second)
n_{LOW}	=	first bin associated with the signal segment
n_{HIGH}	=	last bin associated with the signal segment
N	=	Number of samples used in the DFT
P(n)	=	Power spectrum bins **40**

0082 The signal bandwidth, BW, **17** is calculated with *Eq 4*.

0083 $$BW = (n_{HIGH} - n_{LOW} + 1) * f_s/N \qquad\qquad Eq\ 4$$

0084 The symbols are also needed to reconstruct the signal for transmission. The first step involved to extract the symbols are to a) down convert the signal segments to baseband using the frequency estimate 13 and the bandwidth calculation 17, b) determine the symbol rate 77 and synchronize to the signal to determine the symbols at each symbol period.

0085 When the transmitter of radio **1** is wired to the present system as shown in FIG 2, the received signal is free from interference signals from the environment. In this case, a simpler algorithm such as FM demodulation can be used to determine the carrier frequency. This technique

can not measure the signal bandwidth.

0086 In FIG 5, delay memory **12** is used to give the frequency estimation enough signal duration to obtain a reliable estimate so the entire burst can be analyzed without losing the beginning of the signal.

0087 The down converter block **15** multiplies the digitized signal by a digital local oscillator to down convert the signal to baseband using *Eq 5*. The resultant digital signal at **18** is a complex signal.

0088
$$y_{BB}(k) = y_{IF}(k) * [\cos(2\pi f_c k / f_s) - j \sin(2\pi f_c k / f_s)] \qquad Eq\ 5$$

where
k = sample number: 0, 1, 2, ...
$y_{IF}(k)$ = k'th sample from memory **8**
$y_{BB}(k)$ = k'th complex output down converted sample
f_c = carrier frequency **13** (cycles/second)
f_s = sample rate (samples/second)

0089 The resultant signal at **18** will have one component around 0 Hz and an undesired component centered around $-2 f_c$. The undesired component will be reduced to an acceptable level by lowpass filter **16**. The filter **16** will also decimate the sample rate by M where only the M'th output filtered values are calculated by the filter **16**. For example, in the case of Bluetooth, the hop frequency band covers 83.5 MHz. This band can be digitized with a 200 Msample/second sample rate. The individual hop channels are 1 MHz wide. It is reasonable to reduce the resultant complex sample rate of the baseband signal at **18** from 200 Msamples/second to around 1.25 M complex samples/second. In this case, the decimation factor M is 200/1.25 = 160. The low pass digital filter is either an FIR or IIR filter with bandwidth BW as determined at **17**.

0090 The baseband signal at **18** is processed to measure many of the signal parameters. The first step in the processing is to demodulate the data. The signal can be AM demodulated as shown in *Eq 6*, however, other algorithms can be used to generate the AM signal **20**.

0091 $$AM(n) = sqrt[\ real\{y_D(n)\}^2 + imag\{y_D(n)\}^2\ ] \qquad\qquad Eq\ 6$$

where
n	=	sample number of the decimated samples: 0, 1, 2, ...
$y_D(n)$	=	decimated, filtered baseband complex time samples
AM(n)	=	amplitude waveform **20** of the filtered signal
real	=	extracts the real part of the complex signal
imag	=	extracts the imaginary part of the complex signal

0092 Other parameters may require the phase demodulated signal. The phase demodulated signal can be generated with *Eq 7*; however, other algorithms can be used to generate the phase demodulated signal at output **21**.

0093 $$PM(n) = atan2(real\{y_D(n)\}, imag\{y_D(n)\}) \qquad\qquad Eq\ 7$$

where

n	=	sample number of the decimated samples: 0, 1, 2, ...
$y_D(n)$	=	decimated, filtered baseband complex time samples
PM(n)	=	phase waveform **21** of the filtered signal
real	=	extracts the real part of the complex signal
imag	=	extracts the imaginary part of the complex signal
atan2	=	four quadrant arc tangent function of atan $(imag\{y_D(n)\}/real\{y_D(n)\})$

0094 Other parameters still may require the frequency demodulated signal at output **22**. The frequency demodulated signal may be generated with *Eq 8*, however, other algorithms can be used to generate the FM signal.

0095 $$FM(n) = (f_{sD}/2\pi)\,(PM(n) - PM(n\text{-}1)) \qquad\qquad Eq\ 8$$

where

n	=	sample number of the decimated samples: 0, 1, 2, ...
PM(n)	=	phase waveform **21** of the filtered signal
FM(n)	=	frequency waveform **22** of the filtered signal (cycles/second)
f_{sD}	=	decimated sample rate (samples/second) = f_s/M

0096 Since the FM signal at **22** is derived from the derivative of the PM signal at **21**, any high frequency noise in the PM signal at **21** will be magnified in the FM signal at **22**. It is common to low pass filter the PM signal to reduce the high frequency noise. It is also common to low pass filter the AM signal at **20** and FM signal at **22** to allow more accurate measurements to be made.

0097 If the signal is PSK, the PM waveform at **21** is used to measure the modulation – degrees per symbol state. For example a QPSK signal changes 90 degrees per symbol state. The PM waveform can be used to measure the signal symbol rate, symbol rate drift, modulation depth, jitter, phase accuracy, the symbols and other parameters.

0098 If the signal is FSK, the FM waveform at **22** is used to measure the frequency deviation of the symbol states. The FM waveform is used to measure the signal symbol rate, symbol rate drift, modulation depth, jitter, phase accuracy, the symbols and other parameters.

0099 The symbol rate is a key parameter to all digital signals. Various algorithms can be used to calculate the symbol rate including spectral analysis, correlation and time of transition (TOT) analysis. It is desired to calculate the bit rate independently on each signal segment. TOT analysis is selected as being the most accurate with the short amount of data available in the signal segment. The algorithm that follows is for an FSK signal, however, it is easily adapted for ASK and PSK signals.

00100 FIG 9 shows the algorithm used to calculate the symbol rate on an FSK signal at **22**. The first step in block **60** is to analyze the AM signal at **20** to determine the mean amplitude over the center 75% of the center of the segment. The sample numbers at **62** are identified where the AM signal for the segment exceeds 90% of the mean value. The FM samples associated with these AM sample numbers are stored in memory **63** for processing.

00101 The next step **64** is to remove the mean value of the FM samples. Next the times of each zero crossing **66**, TOT, are calculated in block **65** by interpolating the time of the samples on either side of the zero crossing. The first difference at **83** of the TOTs are calculated in block **67**: $dTOT(k) = TOT(k) - TOT(k-1)$ for all TOTs in the burst.

00102 A histogram of the dTOT values is compiled at **68** and analyzed to find the first major peak **81**, b_{MAX} in block **69**. FIG 15 shows an example of this histogram. There may be stray zero crossings with very short TOT in noisy data that is to be ignored **80**. Harmonic peaks will be present at 2x **82**, 3x **83**, etc. of the fundamental symbol period due to double, triple, etc symbols with the same symbol value. FIG 16 shows an expansion of the first major peak **81** with bins **81-1, 81-2** and **81-3** at dTOT = 49, 50 and 51. The center of mass **84** of the histogram will be the estimate in block **70** of the symbol rate, τ_{est}, at **71**. This estimate is calculated using histograms from about .9* b_{MAX} to 1.1* b_{MAX} which are calculated as shown in *Eq 9*. In the example of FIG 16, the center of mass **84** is (6x49 + 45x50 + 14x51) / (6 + 45 + 14) = 50.12 usec.

00103

$$\tau_{est} = dBin \frac{\displaystyle\sum_{b=.9b_{MAX}}^{1.1b_{MAX}} bHist(b)}{\displaystyle\sum_{b=.9b_{MAX}}^{1.1b_{MAX}} Hist(b)} \qquad\qquad Eq\ 9$$

where:

dBin   =   histogram bin width (seconds)

Hist(b) =   histogram array with bins b

b_{MAX} =   bin number of first major histogram peak

τ_{est} =   estimated symbol period (seconds)

00104 The modulo of the dTOT values at **83** and the estimated symbol rate, τ_{est}, at **71** is calculated in block **72** to remove the double, triple, etc symbols from the dTOT values. An unwrap algorithm is used to correct for +/- τ_{est} errors as shown in the Matlab code of TABLE 2 below. This unwrap algorithm is used if the symbol rate estimate is in error enough so the mod(dTOT) values drift beyond τ_{est}.

00105   TABLE 2

<u>Code</u>   <u>Comment</u>

```
    correction = 0;                    % wrap correction factor
for k = 2:nTOTs;                       % process all TOTs
        dTOT = TOT(k) - TOT(k-1);      % calculate the first difference
        mod_dTOT = mod(dTOT, tauEst);  % calculate the modulo with the
                                             symbol rate estimate
        if mod_dTOT - lastMod_dTOT > tauEst/2;   % value took too high a step
                                                     indicating wrap around
        correction = correction + tauEst;   %
        end                            %
        if mod_dTOT - lastMod_dTOT < -tauEst/2;  % value took too high a step
                                                     indicating wrap around
        correction = correction - tauEst;   %
        end;                           %
        mod_dTOT = mod_dTOT - correction;   %
    end;                               %
```

00106 The resultant mod_dTOT values are fitted to a straight line with a least squares fit **74**.
The resultant slope **75**, m, is used **76** to produce the final symbol rate measurement **77** as shown in
Eq 10.

00107 $\tau_{SYM} = \tau_{est}(1 + m)$ *Eq 10*

00108 The symbol rate is reported to the user. The symbol rate is also used to decode the
individual symbol values and to determine the symbol rate jitter statistics. The first step in this
process is to reconstruct the ideal waveform from the signal. A typical result is shown in FIG 12 with
the FM waveform (shown solid) and the ideal waveform (shown dashed) superimposed, this is the
same signal shown in FIG 10 representing the FM samples in memory **63**. The data shown in FIG 11,
FIG 11 and FIG 12 are the AM and FM demodulated data of the first signal hop H1 shown in FIG
13. The spectrogram analysis shown in FIG 13 and FIG 14 are good for overall visual analysis,
however, they lack the time and frequency resolution for detailed signal analysis. The ideal

waveform is calculated to have the same modulation depth, mean FSK mark and space frequency offsets in this case, the symbol rate at **77** and is synchronized in time to the FSK waveform at **22** (see FIG 5). The jitter is the error between the TOT from the FM waveform and that from the ideal, calculated waveform.

00109 The symbol rate is to decode the individual symbol values. To do this, the time of each zero anticipated symbol transition is calculated from the symbol rate. The time for the ideal first time of transition is calculated with *Eq 11* using the dTOT values **73** and the final symbol rate **77**.

00110 $$\text{Time Offset} = \text{MOD}(\text{dTOT}, \tau_{\text{SYM}})$$ *Eq 11*

00111 The demodulated waveforms in this system are sufficiently over sampled to provide over 10 samples per symbol. The sample at the midpoint of each symbol is determined from the symbol rate and the time offset. The midpoint sample and the samples on either side of this sample are averaged to form the modulation value of the symbol. This is converted to symbol values. In the case of a binary modulation such as common ASK and FSK signals or BPSK signals, the symbol values are arbitrarily assigned to be a "1" if the modulation state is low and to a "0" if the state is high.

00112 The resultant symbols **108** and the hop frequency **13** are stored in storage memory **109** for future use in reconstructing the signal for transmission. Memory **109** is, for example, a computer disk drive.

00113 FIG 6 shows the steps used to generate the signal transmitted to a radio under test. This radio can either be the same radio used to transmit the signal **101-1** or to a second radio **101-2** of the same specification. The first step is for a processor **110** to read the hop information **13** and **108** from memory **109** along with the signal parameters **131** from the system operator. These parameters include carrier frequency error, bit rate error, rise and fall times, amplitude ripple and roll off, modulation depth, nonlinearities, burst duration, burst start time and burst interval. Signal interference can be added to the signal including tones, other signals, noise and other signals of the same as the test radio.

00114 FIG 17 shows the detailed steps to generate the signal to transmit. The first step is for

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the processor to read the signal parameters **131** from the user. This can be done via command line interface, GUI, text files, etc. Some parameters are universal applying to all frequency hop signals, these include carrier frequency error, burst rise time and fall times, rise and fall amplitude vs. time functions, amplitude variation vs. frequency function, symbol rate, symbol rate jitter, hop duration and RMS duration error, hop to hop interval and RMS interval error and interference signal types, frequencies and amplitudes.

00115 Other parameters are unique to the signal type being generated. For example, an FSK signal will require information on the nominal frequency offset for the two states along with the RMS frequency error, the bandwidth of the modulated signal, symbol structure such as if the burst comes up with an unmodulated carrier or starts with the first symbol, are the symbols phase continuous, frequency overshoot at symbol transitions, etc.

00116 Once the system has the signal parameters, it can start to build the signal. The system reads the first hop frequency **13** and symbol set **108** stored earlier in memory **109**. These values are used by the generation process **133**, along with the signal parameters, to generate the digital signal time samples. The details of this generation process are unique to each signal type. For example, a Bluetooth FSK signal may be generated with different algorithms than a military SINCGARS FSK signal. The processes to generate each of these signals are provided by the physical layer specifications of the individual radios and signals. Generically this process consists of generating a carrier modulated with the symbols at the symbol rate specified, filtering the resultant carrier, frequency converting to the hop frequency **13**, converting from complex to real data if necessary and scaling the amplitude for output to the D/A.

00117 The signal generation process can add in interference signals and noise. The interference signals can be simple as tones or complex signals. For example Bluetooth operates in the 2.4 GHz ISM band that is also used by many other systems including 802.11b/g wireless networks, cordless phones and microwave ovens. Each of these can produce harmful interference signals. The present system can simulate these signals and add them to the generated signal. These interference signals can be added in either digitally on the digital signal in generator **110** or with analog signal generators and summing circuits following the D/A converter **111**. The interference could also be another radio of the same type as the test radio operating in the same frequency band.

00118 The system can generate and add noise to the generated signal. This will simulate receiving a weak signal that can have significant background noise. This noise is typically white Gaussian noise. The noise can be added in either digitally on the digital signal in generator **110**, or with an analog noise generator summed in to the signal after the D/A converter **111**.

00119 The system can change the amplitude of the signal dynamically to simulate the fading that is encountered by moving transmitter or receiver. At some frequencies rain can cause fading that can be simulated. The fading can be produced either digitally on the digital signal in generator **110**, or in analog with variable attenuators after D/A converter **111**.

00120 The form of the signal could be either real or complex values. In the preferred embodiment, the samples are real values at a baseband IF frequency band.

00121 The resultant time samples are written to the D/A memory and the D/A is commanded to start playing the data in memory. After the first hop is generated, the system returns to read the data on the next hop **13** and **108** and continues.

00122 The radio receiver **101** or **101-2** is monitored at **99** to determine if it detected and processed the signal properly. This monitoring can be as simple as the operator listening to the radio speaker to determine if the same voice message sent **114** was received **115** and heard properly.

00123 The monitoring could be automated with some radios where a specific digital message is transmitted **114**, processed by the system and retransmitted **115** to radio. The radio **101** or **101-1** output is compared against the transmitted digital message to detect any bit or symbol errors. Some radios produce diagnostics that can be used to determine any issues with receiving and processing the transmitted signal.

00124 In FIG 18, a sequence of tests is performed. First the send test signal at **101-1** sends a test signal like the transmission from radio **101-1** in FIG. 3, for example. The test signal is received and analyzed in **142**. Based upon the analysis, a modified test signal is formed at **143** under control of control **100**. The send modified test signal sends a test signal and the test signal is received at **101-2**, like the reception of radio **101-2** in FIG. 3 and the reception by the radio is tested at **99**. The sequence of FIG 18 is repeated as many times as is useful whereby sequential modification of the test signals occurs to determine what elements of a radio's operation are causing problems.

00125 While the invention has been particularly shown and described with reference to

preferred embodiments thereof it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention.